Spontaneous CPT asymmetry of the Universe*

A.A.Andrianov[1,2], P.Giacconi[1], R.Soldati[1]
[1] Dip. di Fisica & INFN, Univ. di Bologna, via Irnerio 46, 40126, Bologna
[2] Dept. of Theor. Phys., V. A. Fock Inst. of Physics, 198504, St.Petersburg

The extended QED with renormalizable interactions breaking the Lorentz and CPT symmetry is considered and the phenomenological consequences of such a symmetry breaking are illuminated in view of recent discussion of large scale anisotropy of the Universe. Other physical effects in QED with CPT violation are examined, in particular, mass splitting between electrons of different helicities and decay of very high energetic electrons into lower energy electrons and positrons.

So far the Lorentz symmetry has been proven to hold with a very high accuracy. Nevertheless, one can inquire about whether the Special Relativity Theory is only approximate. The modern, quantum field-theoretical approach admits that the *spontaneous* Lorentz symmetry breaking is not excluded. At this expense the CPT symmetry can be also broken in a local field theory.

The occurrence of a very small deviation from the Lorentz invariance has been discussed recently [1-3], within the context of the Standard model of electroweak interactions. There, some "background" or "cosmological" fields are implied , leading to deviations in the propagation of certain particles, within the present experimental limits.

As the photon is a test particle of the Special Relativity the most crucial probes concern Lorentz- and CPT-symmetry breaking modifications of electrodynamics.

When one retains its fundamental character provided by renormalizability and the gauge invariance of its action, then it might be induced in the ordinary *3+1* dimensional Minkowski space-time by supplementing QED with the additional CPT-odd Chern-Simons (CS) coupling of photons to the vacuum [1] mediated by a constant CS vector η_μ. This modification of Electrodynamics does not break the gauge symmetry of the action but changes the dispersion relations for different photon polarizations [1]. As well a constant axial-vector field b_μ may couple to the fermions [2] splitting their masses and breaking the CPT and Lorentz symmetry.

All together the minimal modification of QED is given by the following lagrangian,

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - Bn_\mu A^\mu - \frac{1}{2}\eta_\mu A_\nu \tilde{F}^{\mu\nu} + \bar{\psi}\left(i\gamma^\mu\partial_\mu + e\gamma^\mu A_\mu - m - \gamma^\mu\gamma_5 b_\mu\right)\psi \qquad (1)$$

in the axial gauge. The Lorentz and CPT symmetry breaking is parameterized by two vectors η_μ and b_μ which are not necessarily collinear. Their dynamical origin represents an interesting problem and one of the possible ways to induce LSB by a dynamical mechanism has been suggested recently [4]. Namely, the spontaneous breaking of the Lorentz symmetry *via* the Coleman-Weinberg mechanism [5] has been proved for a class of models with the Wess-Zumino interaction between abelian gauge fields and pseudoscalar

*Talk at V International Conference on Cosmoparticle Physics COSMION-2001, dedicated to the 80-th Anniversary of Andrei D. Sakharov (Moscow-St. Petersburg, May 21-30, 2001)

massless axion $\theta(x)$(AWZ models). Then the condensation of the gradient of axion field $< \partial_\mu \theta > \sim \eta_\mu \sim b_\mu$ may be a natural implementation for LSB [6] just relating its origin to the existing "quintessence" fields [7]. On the other hand, a part of the background vector b_μ may represent the constant torsion $b_\mu \sim \epsilon_{\mu\nu\rho\sigma} T^{\nu\rho\sigma}$ in the large scale Universe [8-10].

When having the modified QED (1) one searches for the phenomenological consequences of the symmetry breaking which can be registered in the experiments. As well one should examine the consistency of this QFT (stability [4,11,12] and microcausality[11,13]) once the latter one pretends to describe the particle physics in a wide range of energies.

Distorted photons

In the CPT odd QED the *linearly* polarized photons created in the Universe may reveal the birefringence [1], *i.e.* the rotation of the polarization direction depending on the distance, when they propagate in the vacuum. The consistent QED exists only for *space-like* CS vectors $\eta^2 < 0$ (in the presence of fermions one has also to take into account the radiatively induced CS term [12,14]) and it can be canonically quantized in the frames where this vector is entirely space-like, $\eta_0 = 0$ (see[4,12,13]). In this case there are always four real solutions of the equation for energy spectrum

$$k_{0\pm}^2(\vec{k}, \vec{\eta}) = \vec{k}^2 + \frac{1}{2}\vec{\eta}^2 \pm |\vec{\eta}| \sqrt{(\vec{k} \cdot \vec{\eta})^2 + \frac{1}{4}\vec{\eta}^2} \ . \tag{2}$$

As it can be seen for very small wave vector $\vec{k}$ two photon modes (the "left" ones) remain massless and other two (the "right" ones) become massive. Therefore monochromatic plane wave solutions are possible only with a definite chiral polarization whereas the linearly polarized photons reveal the rotation of the polarization direction in time = with a distance. We stress that in the case of CPT odd QED the notion of handedness or chirality which is conserved only approximately corresponds to that one in the Maxwell QED, i.e. the left-(right-)handed photons do not have exactly circular polarizations [1,2,15]. Meanwhile the group velocities for these modes turn to be always smaller than c. This supports a birefringence phenomenon, because the group velocities of the linearly polarized wave-packets made out of chirally polarized CS-photons are smaller than c.

The earlier analysis of radiowaves from distant galaxies had been performed [1] in the assumption of purely time-like LSB when $\vec{\eta} = 0$ which however is not consistent at the quantum level. The space-like scenario was recently reexamined [16,17]. The present situation can be conservatively characterized by an upper bound, $|\vec{\eta}| \leq 10^{-32} eV$.

Fermions in the constant axial field

The consistent Dirac-type quantization of massive fermions in the constant axial-vector background is frame-dependent and available for *time-like* $b^2 > 0$ if the space part is small $\vec{b}^2 < m^2$. In this case one has four real solutions: two of them with positive energies and

other two with negative energies [12]. In the rest frame of $b = (b_0, 0, 0, 0)$ their dispersion law is

$$p_0 = \pm\sqrt{(|\vec{p}| \pm |b_0|)^2 + m^2}; \quad p^2 = b_0^2 + m^2 \pm 2|b_0||\vec{p}|. \tag{3}$$

One can see that a pair of solutions of a definite helicity always describes the massive particle but another pair of opposite helicity corresponds to a massive particle only for $|\vec{p}| < (b_0^2+m^2)/2|b_0|$. Above this bound the phase velocity exceeds the conventional speed of light c. Nevertheless if $b^2 > 0$ then the group velocity turns out to be $< c$.

Thus in such a theory the two characteristic scales arise: one is supposedly small $|b_\mu| \ll m$ and another one is extremely high $M \simeq m^2/2|b_0| \gg m$. Respectively two phenomena occur at low and high energies. The first one is the mass splitting between electrons of different helicities ($\pm$ in (3)). if the value of b_0 is universal for all fermions, then the lightest massive ones - electrons and positrons - should give the best precision in its determination. As the precision of a measurement of the electron mass [18] is of the order 10^{-8}, the upper bound on the time component of CPT breaking vector is not very stringent: namely, $|b_0| < 10^{-2}$ eV (or even weaker, being controlled by the energy resolution in accelerator beams). On the other hand, some much more stringent bounds were obtained for space components of b_μ, from the experiments with atomic systems using hydrogen masers [19] - *i.e.* $|\vec{b}| < 10^{-18}$ eV - and with a spin-polarized torsion pendulum [20] - *i.e.* $|\vec{b}| < 10^{-20}$ eV.

The second phenomenon takes place at very high energies, $M > m^2/|b_0| \simeq 10^2 TeV$ when some of electron states obtain the space-like energy-momentum. Then conventional wisdom of relativity theory fails and a high energetic electron may well decay into an electron of the same helicity and a pair of positron and electron of the positive and negative helicities respectively. This process starts for $|\vec{p}| > 2m^2/|b_0|$ and the final momenta of particles are roughly three times less than the initial momentum. Such a process will "wash out" from the asymptotic states very high energetic electrons and positrons and therefore the natural momentum cutoff arises being stuck to the rest frame of the vector b_μ. The ultraviolet divergences are then cured by this physical cutoff and the effective CS vector radiatively induced by one fermion loop is defined uniquely [12], independently on renormalization scheme (compare to [14,21]),

$$\Delta\eta_\mu = \frac{2\alpha}{\pi}\sum_{a=1}^{N} b_\mu^a, \tag{4}$$

where the summation has to be performed over all the N internal charged fermions degrees of freedom and the possibility to have different axial charges for different fermions is taken into account.From the recent experimental bounds obtained in Refs. [19,20] it is possible to estimate the magnitude of the spatial components of the induced CS vector to be of the order $|\Delta\vec{\eta}| < 10^{-19}$ eV, under the assumption that all the vectors $\vec{b}^a$ are of the same order. If the vectors b_μ^a are related to some background torsion, then one expects them to be identical. If, however, they are generated by *e.g.* vacuum expectation values of gradients of axion fields, then it is conceivable that b_μ^a might have different values.

Consistency between photons and fermions

The consistent quantization of fermions in a constant axial-vector field asks for the vectors b^a_μ to be time-like [11, 12] which, nevertheless, does not mean that the sum in eq. (4) is also time-like, because some of the fermions may have the opposite axial hypercharges.

On the other hand, the consistent quantization of photons can be achieved when the full *dressed* CS vector $\tilde{\eta}_\mu = \eta_\mu + \Delta\eta_\mu$ turns out to be essentially purely space-like [12,13].

As we suppose that there is some dynamical mechanism to generate - with the help of axion condensation - the purely bosonic part η_μ of the full CS four-vector, the compatibility of the consistent quantization of both fermions and bosons is believed to be quite possible, contrary to the claim in Refs. [13].

However, from the practical point of view, the cancellation between time components of η_μ and $\Delta\eta_\mu$ should be extremely precise, in order to satisfy the experimental bounds [1,16,17] and to fulfill the microcausality requirement of the photo-dynamics. As well the severe experimental bounds on $\vec{b}^a$ for electrons, and protons [19,20], together with the estimation of birefringence of radio-waves from remote galaxies and quasars[1,16,17], do not leave too much room to eventually discover the CPT and Lorentz symmetry breaking in the quantum spinor and photon dynamics.

A. A. A. is partially supported by Grant RFBR 01-02-17152, Russian Ministry of Education Grant E00-33-208 and by The Program *Universities of Russia: Fundamental Investigations* (Grant 992612); P. G. is supported by Grant MURST-Cofin99.

References

[1] S. M. Carroll, S.M., Field, G.B., and Jackiw, R. 1990, Phys. Rev. **D41**, 1231

[2] Colladay, D. and Kostelecký, V.A., 1997, Phys.Rev. **D55**, 6760; 1997, Phys.Rev. **D58** 116002, and references therein

[3] Coleman, S. and Glashow, S.L. 1999, Phys.Rev. **D59**,116008

[4] Andrianov, A.A. and Soldati, R. 1995, Phys.Rev. **D51**, 5961;
1997, Proc. 11th Int. Workshop QFTHEP96, St.Petersburg,Russia, 12-18 Sept. (MSU Publ., Moscow, 1997) 290;
1998, Phys.Lett. **B435**, 449

[5] Coleman, S. and Weinberg, E. 1973, Phys.Rev. **D7**, 1888.

[6] Andrianov, A.A., Soldati, R. and Sorbo, L. 1999, Phys.Rev. **D59**, 025002

[7] Carroll, S.M. 1998, Phys.Rev.Lett. **81**, 3067

[8] De Sabbata, V. and Gasperini, M. 1981, Phys.Lett. **A83**, 115

[9] Carroll, S.M. and Field, G.B. 1994, Phys.Rev. **D50**, 3867

[10] Dobado, A. and Maroto, A.L. 1997, Mod.Phys.Lett. **12**, 3003

[11] Kostelecký, V.A. and Lehnert, R. 2001, Phys.Rev. **D63**, 065008

[12] Andrianov, A.A., Giacconi, P. and Soldati, R. 2001, [hep-th/0110279]

[13] Adam, C. and Klinkhamer, F.R. , 2001, Nucl.Phys. **B607**, 247; 2001, Phys.Lett. **B513**, 245

[14] Jackiw, R. and Kostelecký, V.A.,1999, Phys.Rev.Lett. **82**, 3572

[15] Klinkhamer, F.R. , 2001, [hep-th/0110135]

[16] Nodland, B. and Ralston, J.P., 1997, Phys.Rev.Lett. **78**, 3043

[17] Carroll, S.M. and Field, G.B., 1997, Phys.Rev.Lett. **79**, 2394;
Wardle, J.F.C., Perley, R.A. and Cohen, M.H., 1997, Phys.Rev.Lett. **79**, 1801;
Loredo, T.J., Flanagan, E.E. and Wasserman, I.M., 1997, Phys.Rev. **D56**, 7507

[18] Particle Data Group, Groom, D.E. *et al*, 2000, Euro.Phys.J. **C15**, 1

[19] R. Bluhm, V. A. Kostelecký and N. Russell, Phys. Rev. Lett. **82** (1999) 2254;
M. A. Humphrey *et al.* [physics 0103068].

[20] E. G. Adelberger *et al.*,, 1999, in *Physics Beyond the Standard Model*, P. Herczeg *et al.* Editors, World Scientific, Singapore, p.717.

[21] M. Pérez-Victoria, 2001, JHEP **0104**, 032, and references therein